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LLNL-TR-608814

# Next-Generation Tunable Targets for Laser--Compression Experiments

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December 19, 2012

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This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

## Final Report

### *Next-Generation Tunable Targets for Laser-Compression Experiments* *NIF Concept Development Proposal: 2011-2012*

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With the advent of high-power lasers, it is now possible to experimentally characterize materials at exceptionally high dynamic compressions, exceeding 10-100-fold initial density. This takes matter into the atomic-pressure regime (29 TPa), where new physics is anticipated and first-principles calculations can be validated to an unprecedented degree. Such pressures are also achieved inside and during the formation of planets, so the material properties that can now be characterized are directly relevant to understanding the origins and evolution of planets.

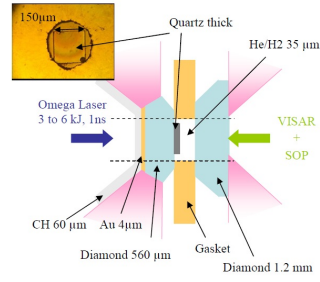
Our group has pioneered methods for tuning the final states that can be achieved on dynamic compression, from single-shock (Hugoniot), to multi-shock and ramp compression. In addition, we can tune the final state by changing the initial density, through a combination of pre-compression and cooling or heating the sample. Such tuning allows us to achieve much higher densities (lower temperatures) than is possible in traditional Hugoniot experiments, thereby greatly extending the range of conditions over which theory can be validated. Hence, the results can be applied to understanding planets: because planetary interiors are largely isentropic, our reduced-temperature measurements are more directly relevant than are shock measurements. We can uniquely study mixtures of fluids – important for planetary science, chemical physics and other disciplines – and our tuning allows us to separately characterize thermal from compressional effects on material elasticity, bonding, electronic properties and phase stability.

A more subtle but important development is that we can quantify the differences between different paths to nominally similar off-Hugoniot state. That is, we can contrast the results obtained using ramp compression, multiple-shock compression or a pre-compressed sample to achieve a given stress–density state. We are finding indications that there can be significant differences between nominally similar off-Hugoniot states, directly challenging some of our fundamental approaches to understanding dynamic compression. These results may be relevant for ICF and other important applications.

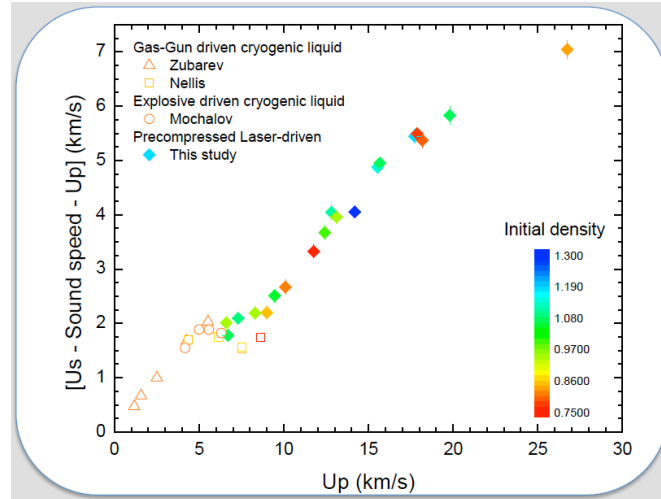
The project supported a CEA-LLNL-UCB development of new pre-compressed target capability, and specifically supported Dr. Marius Millot, a postdoctoral researcher at UC Berkeley who has worked at Janus (LLNL) and Omega (Rochester) during the funded period.

#### *New Designs for Pre-Compression*

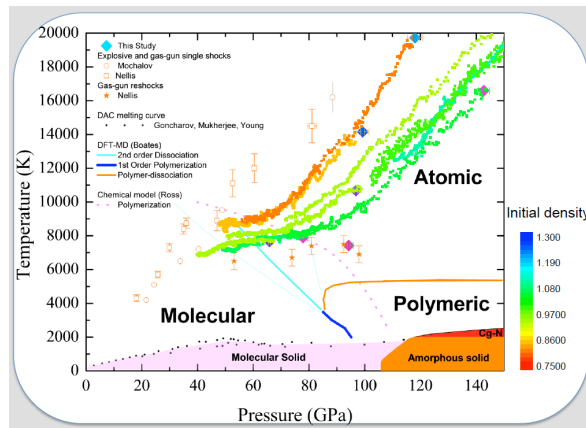
We have developed and implemented new designs of diamond-anvil cells that now allow us to pre-compress hydrogen and hydrogen mixtures to the 20 GPa range (Fig. 1), a significant improvement over the 2 GPa limit of our earliest experiments. The typical sample diameter is now 200  $\mu\text{m}$  in diameter, and the backing plates are optimized both for optical access of drive-laser beams and for mechanical stability of the anvils. The cells have been tested and calibrated, and have now been used in several experiments at Omega.



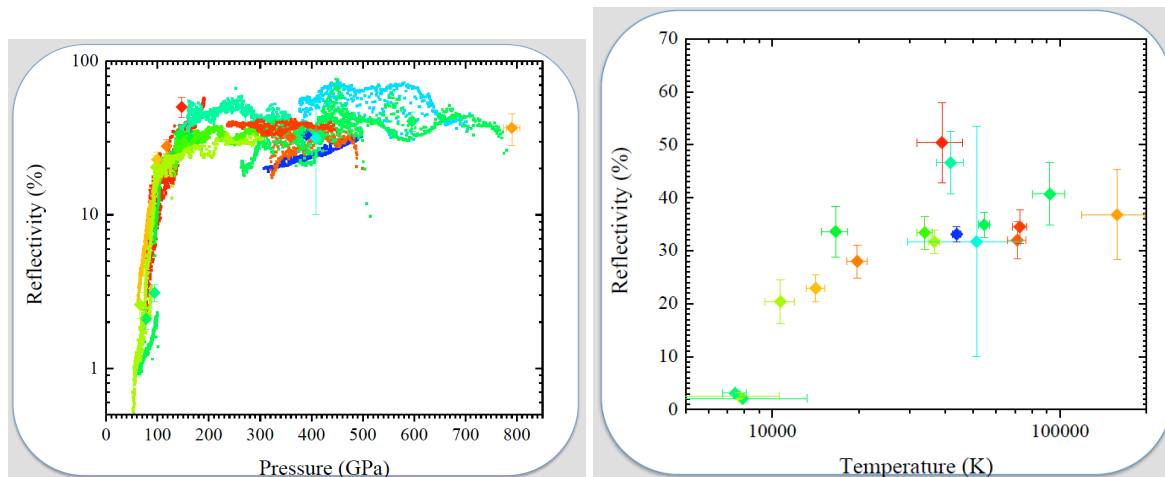
**Figure 1.** Diamond-anvil cell configuration for pre-compression (SOP is streaked optical pyrometer).



**Figure 2.** Hugoniot data obtained for nitrogen, illustrating good agreement with past measurements at low pressures, as well as evidence for significant changes in the fluid state at higher pressures ( $u_p > 5-7$  km/s and  $u_p > 15$  km/s). For clarity, a reduced shock-wave velocity ( $U_s$ ) is plotted as a function of particle velocity ( $u_p$ ).



**Figure 3.** Comparison with previous data and phase diagram of nitrogen at low pressures (below 150 GPa) shows good agreement with our measurements, and illustrates the effects of pre-compression. For the present experiments, large symbols with error bars indicate temperatures measured by SOP and smaller symbols are for temperatures derived by interpolation.



**Figure 4.** Reflectivity of nitrogen as a function of pressure (*left*) and measured temperature (*right*), documenting the onset of metallic character above 150 GPa and 15,000 K.

### *Application to Nitrogen*

We have applied our methods to samples of  $N_2$ , motivated by interest in physical chemistry and planetary science. Also, pioneering work by Nellis and others documented dissociation of nitrogen under shock compression, thereby providing a good test-bed for validating our approach.

Our temperature-dependent dynamic-compression measurements are in good agreement with prior experiments, and greatly extend the range of densities, pressures and temperatures over which the equation of state and optical properties of nitrogen are now characterized (Figs. 2-4). Our results are consistent with previous single- and double-shock compression measurements indicating dissociation (Fig. 3), and also show evidence of significant bonding changes in the fluid (Figs. 2 and 4). In particular, reflectivity saturating at 30-50 percent is indicative of metallization in the fluid state.

Nitrogen is an important constituent of planets, both on its own and in ammonia and other compounds. The electron mobility documented here shows nitrogen can help sustain magnetic-field generation (i.e., dynamo action) inside giant and super-giant planets, such as those being documented in great abundance nearby in our galaxy. Our data are also applicable to modelling the interiors of Uranus and Neptune in our own Solar System.

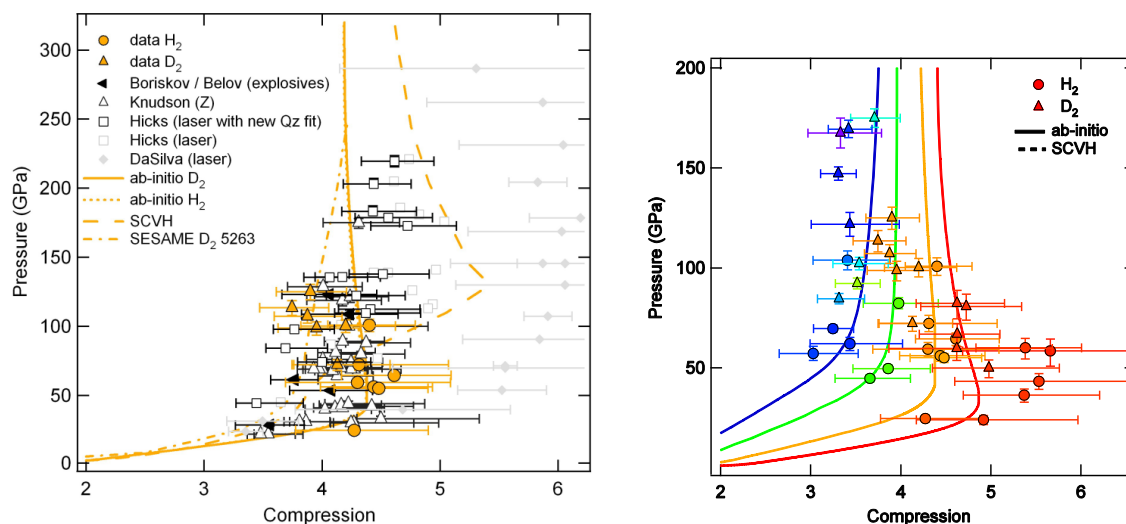
These results have been presented at a Gordon Conference, and publication is underway.

### *Other Findings*

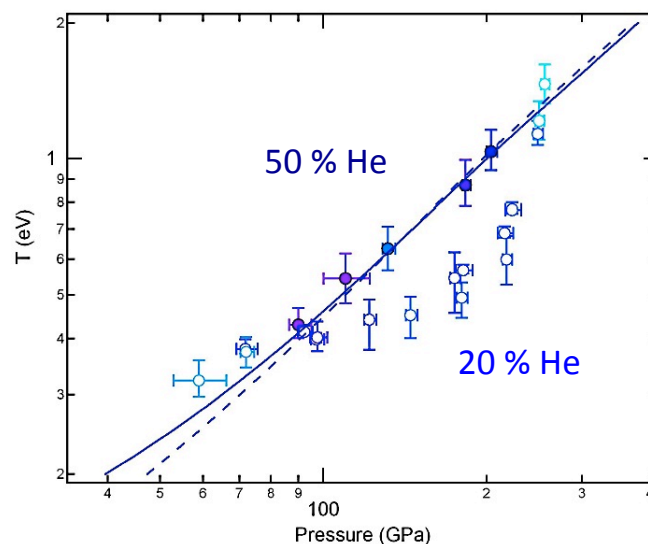
We made a significant discovery, with the finding that shock-compressed hydrogen-helium mixtures do not behave as would be expected by simply combining results for hydrogen and helium alone. This result is important because it provides the first experimental evidence for a longstanding theoretical prediction that hydrogen-helium fluid mixtures can undergo unmixing at high pressures, the implication being that helium can separate from hydrogen inside giant planets: the resulting “differentiation” (compositional

unmixing) can release significant gravitational energy, and is thought to have greatly influenced the evolution of Saturn relative to Jupiter.

This work requires pre-compression, in order to study well-characterized mixtures of the  $\text{H}_2$ –He fluid mixtures, and it depends on a large amount of data being collected on the separate end-members ( $\text{H}_2$  and He) as well as on mixtures of different composition (Fig. 5).



**Figure 5.** Principal Hugoniot for  $\text{D}_2$  (left): at 0.3 GPa and 300 K, the density of  $\text{D}_2$  and  $\text{H}_2$  is the same as that of cryo-samples, hence the associated Hugoniot points should fall on the same curve; summary of  $\text{H}_2$  and  $\text{D}_2$  results for pre-compressions ranging from 0.16 GPa (red) to 1.6 GPa (blue) (right). Our data agree with measurements obtained on independent platforms (Z, converging explosives and laser with cryogenic targets).



**Figure 6.** Temperature versus pressure along the Hugoniots of equimolar and 20 mol% He concentration  $\text{H}_2$ /He mixtures (4 GPa initial pre-compression), shown as filled and open symbols, respectively.

The key measurements, summarized in Fig. 6, show that an 80:20 H<sub>2</sub>:He mixture has much lower shock temperature between 90 and 250 GPa than does an equimolar mixture. The shock-response of the 50:50 H<sub>2</sub>:He mixture is that which would be expected from ideal mixing of the end-members, and the reduced temperature for the hydrogen-rich mixture can be attributed to unmixing. Giant planets are characterized by hydrogen-rich H<sub>2</sub>:He mixtures, so our findings are directly relevant to understanding the combined thermal–unmixing evolution of their interiors.

This work has been reported at the Gordon Conference, and is being prepared for publication.

#### *Publication*

P. Loubeyre, S. Brygoo, J. Eggert, P. M. Celliers, D. K. Spauldin, J. R. Rygg, T. R. Boehly, G. W. Collins and R. Jeanloz, An extended data set for the equations of state of warm dense hydrogen isotopes, submitted for publication (2012).